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Van Peteghem, Hugues; Schumacher, Laurent

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Description of an IPv6 Linux-Based UTRAN Testbed

Van Peteghem H. and Schumacher L.
Pôle "Réseaux et Sécurité"
The University of Namur, FUNDP
Namur, Belgium
{hvp, lsc}@info.fundp.ac.be

Abstract—Network modelling and traffic characterisation are essential research activities towards the optimisation of UMTS. We present here our IPv6 Linux-based UTRAN testbed which aims at emulating a real UTRAN segment. This emulation is relying on statistical traffic distributions, random walk UE mobility and line-of-sight power-based handover management. By interconnecting those different modules, we expose the first testbed results about the handover management and our views regarding the QoS management.

Index Terms—UTRAN emulator, testbed, traffic modelling, terminal mobility, handover.

I. INTRODUCTION

The evolution of mobile communications and the Internet has lead to the third generation of cellular networks (3G), known as Universal Mobile Telecommunications System (UMTS). With the launch of this new generation of mobile communication, users are now truly able to access the Internet from mobile terminals, allowing them to enjoy a large variety of added value services.

In this context, UMTS Terrestrial Radio Access Network (UTRAN) modelling and traffic characterisation are important steps of the research. The goal of our project is to provide a representative testbed which emulates a real UTRAN segment supporting typical traffic samples based on significant statistical properties. This gives us a tool able to emulate real UTRAN behaviours with more realism and less theoretical hypotheses than simulators (ns-2 or opnet), and less costs than a real UTRAN deployment. Such a testbed will be useful to investigate issues like Quality of Service (QoS) or Radio Resource Management (RRM). The objective of this paper is to present the first release of our testbed, its implementation and the first results.

The rest of this paper is organised as follow. Section II presents the testbed architecture. Section III describes the supported traffic classes. Section IV depicts our world representation, explains how we emulate mobility above a wired network infrastructure and exposes the testbed handover management. Section V then presents the first results obtained. Section VI discusses the main future work items. Finally conclusions are drawn in Section VII.

II. TESTBED DESCRIPTION

As shown on the upper part of Fig. 1, we emulate a UTRAN segment consisting of one Radio Network Controller (RNC) managing four NodeBs each of them serving a population of User Equipments (UEs). The NodeBs are placed on a hexagonal grid but, for representation simplicity, the four cells are represented on a rectangle map.

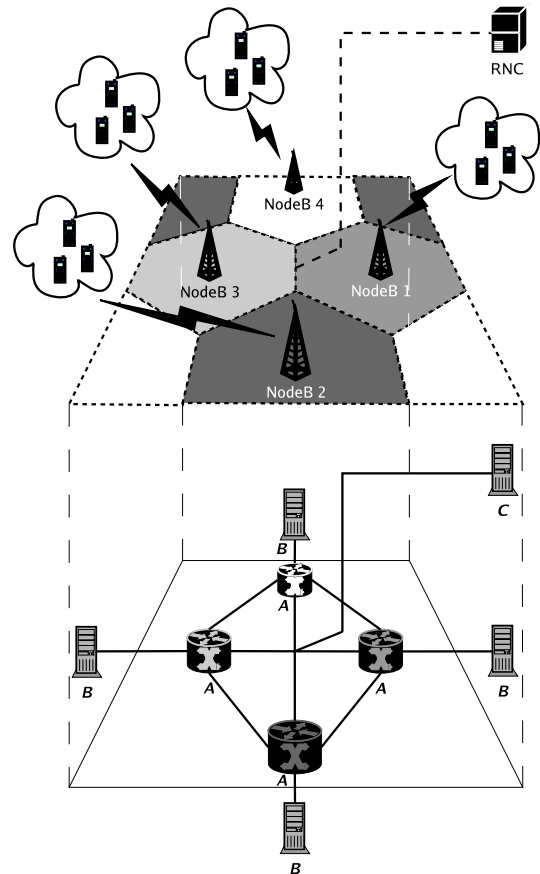


Fig. 1. UTRAN testbed representation.

In order to emulate this UTRAN segment, we have built a testbed which is composed of nine Linux personal computers interconnected with 10 Mb/s Ethernet links, as shown on the lower part of Fig. 1. It is formed by three groups of computers, namely A, B and C.

The first one, the *A* group, is made of Pentiums III 750 MHz with 512 MB of RAM. They all have four network interfaces connected to various sub-networks. The *B* group is composed of Celerons 300 MHz with 64 MB of RAM. Each one is connected to one of the computers of the *A* group. Finally, the *C* group, which is in fact composed of a single computer, has the same hardware specification as the *A* group computers and is directly connected to all the *A* group machines. For the sake of homogeneity, we have installed the same operating system on each machine: a Linux Red-Hat based Fedora Core 1, kernel 2.4.26.

The *A* group is placed in the centre of the network. These computers are used as routers running the routing freeware *Quagga* [1], whereas the computers of the *B* and the *C* groups are placed in periphery and used as traffic sources/sinks. To serve that purpose, we have installed the open-source application *TG* [2] which is a traffic generator program able to create one-way UDP or TCP streams between two computers. This traffic is detailed in Section III in terms of inter-arrival times and packet lengths with the help of statistical distributions.

Using this testbed, the idea is to mimic the working of a real UTRAN segment:

- The *A* group computers act as the NodeBs. Their role is to take care of the traffic coming from the UE (resp. RNC) and to forward it to the RNC (resp. UE). Most of the QoS management functions will be performed at these spots since they are the bottlenecks of the UTRAN (border between the wireless and the wired networks). Actually, in the early UMTS standardisation the NodeBs were seen as simple access points linking the UEs to the UTRAN and the Core Network (CN). But, since the High Speed Downlink Packet Access (HSDPA [3]) introduction, they have much more responsibilities in terms of QoS management and packet scheduling.
- Each computer of the *B* group represents a population of UEs attached to their serving NodeB (emulated on the attached *A* group computer). Each of them will generate several uplink flows (from the UE to the RNC). In order to simultaneously emulate several autonomous UEs, we implemented a control panel based on virtual network interface management. The role of this control panel is to facilitate the UE management by delegating them a single IP address.
- The *C* group computer plays the role of the RNC. It will be the sink of the traffic coming from the four NodeBs and will generate the downlink traffic (from the RNC to the UEs). As in a real UTRAN, the complexity is gathered in the RNC. It consequently controls the entire emulation.

III. TRAFFIC GENERATION

In [4], the 3rd Generation Partnership Project (3GPP) has defined four classes of services that need to be supported in UMTS. In order to characterise them, it might be useful to focus ourselves on four representative applications (Table I):

TABLE I
TRAFFIC CLASSES AND APPLICATIONS.

3GPP Traffic Classes	Representative Applications
Conversational	VoIP
Interactive	Web browsing
Streaming	Video streaming
Background	E-mail

Several studies have already been done about UMTS traffic modelisation [5], but none of them characterised simultaneously all four traffic classes. Most of them consider only two classes, namely conversational and interactive. Although these traffic classes will certainly be the most popular, our aim is to be able to emulate any UMTS traffic mix.

To characterise the composite traffic of a single user, we fit each representative application in a three-level model shown on Fig. 2 [6]. Here is a quick run-down of their meaning:

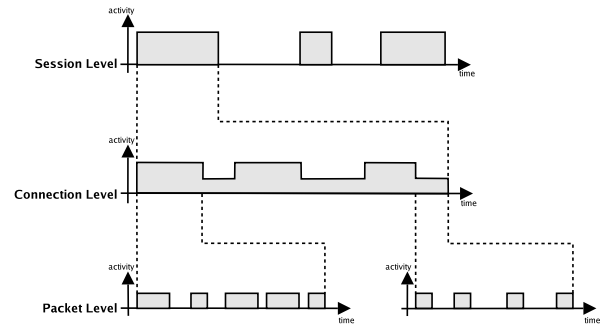


Fig. 2. Three-level traffic model.

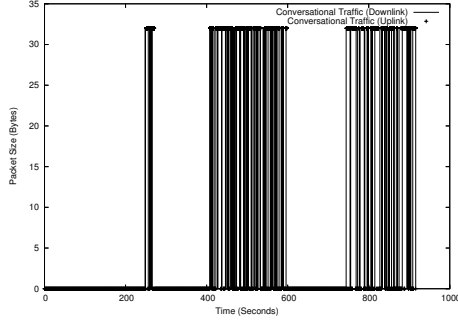
- Session Level: it lasts as long as the application is running. Its statistics are mainly influenced by user behaviour.
- Connection Level: it describes the connection behaviour of a single session. The pattern chosen for our sources is based on an On-Off (High-Low) model in which it could be possible to generate traffic on both states.
- Packet Level: it represents the packet inter-arrival and size distribution for each state of the Connection Level.

As an example to illustrate this three-level model, let us consider the conversational class. In this case, the session level describes the moments when a user is engaged in a phone call and the moments when s/he is not. When the user is engaged in a call, the connection level represents the time intervals during which the user is speaking and the time intervals during which s/he is simply listening. Finally, when the user is speaking, the packet level gives the size of each packet sent and the time interval separating two successive packets.

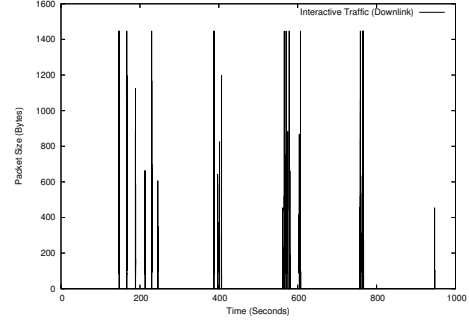
Based on this three-level division, the four traffic classes are described in terms of statistical distributions, in line with literature [7]–[10] and 3GPP standards [11]–[13] when applicable. These descriptions are summarised in Table II.

TABLE II
TRAFFIC CLASSES STATISTICAL DISTRIBUTIONS.

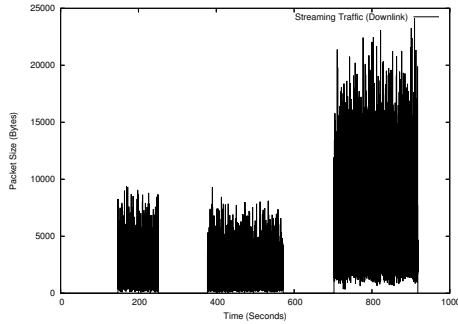
Classes	Session-Level	Connection-Level	Packet-Level
Conversational	Poisson	Two States Markovian	Constant
Interactive	Poisson	Geometric & Exponential	Pareto & Exponential
Streaming	Poisson	—	Pareto
Background	Poisson	Lognormal & Pareto	Lognormal



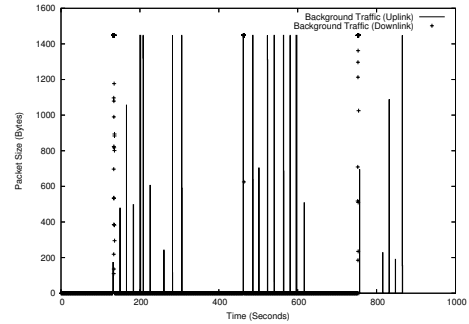
(a) Conversational.



(b) Interactive.



(c) Streaming.



(d) Background.

Fig. 3. UE activity graphs.

This probabilistic model of the traffic is used in the testbed to initiate sessions of any of the four traffic classes at any time in accordance to Poisson processes. It means for example that an emulated UE may very well initiate a conversational session while already having an ongoing interactive session. This would be translated in a real UTRAN by the fact that an UMTS user gets called as s/he was browsing the Internet on his/her 3G terminal.

Before generating these different traffics, we had to modify the *TG* source code to support the Pareto distribution and the IPv6 addressing¹. As a matter of validation, we simulated a single UE connected to a NodeB, generating and receiving all kinds of traffic during 1,000 seconds. Fig. 3 depicts the activity graphs of each of the four classes.

¹The validation of the Pareto distribution implementation and the new version of *TG* are available on: http://www.info.fundp.ac.be/~hvp/rech/doc/index_en.html

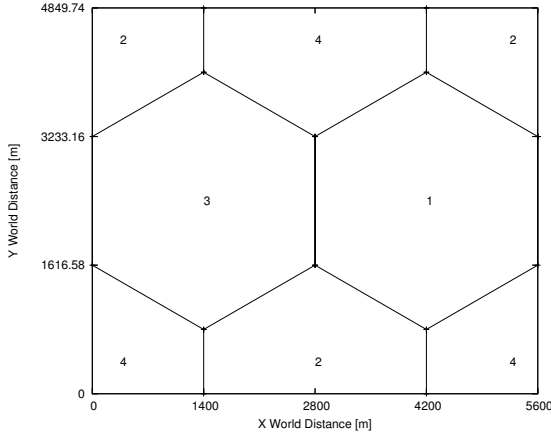
Note that we only emulate uplink traffic for the applications emitting a significant amount of data. Consequently, as we can see on Fig. 3(a) and 3(d), the uplink direction of traffic is emulated only for the conversational and background classes. Interactive uplink traffic (mainly constituted of TCP acknowledgements) is not emulated.

There is a need of synchronisation for these two bidirectional traffic classes. Indeed, in a real conversation both of the participants are speaking throughout the session. Therefore, the emulated downlink and uplink traffics have to be synchronised and mixed. In the background case, we can think of a user downloading his/her mails and answering some of them one by one after their download. In this case, the emulation begins with a downlink traffic followed by multiple smaller uploads.

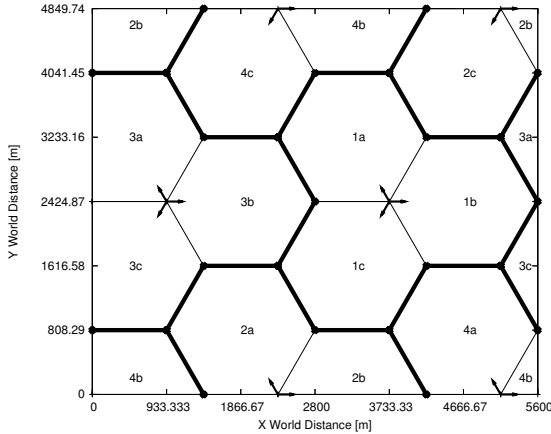
IV. MOBILITY MANAGEMENT

A. Emulated World

As previously mentioned, we emulate a UTRAN segment consisting of four cells. We decided to place the NodeBs at 2,800 meters away from each other on an hexagonal grid which is the standard macrocellular set-up [14], [15]. This means that the cell radius equals 1,400 meters and the total surface of the four emulated cells is about 27 km^2 . But in a real world the NodeBs are not omnidirectional, they are composed by three sectors emitting in different directions. This leads us to adapt our world representation. Fig. 4 depicts the world evolution from the omnidirectional to the trisectorial NodeBs. On Fig. 4(b), the arrows represent the sector's main emitting directions.



(a) Omnidirectional NodeBs.



(b) Trisectorial NodeBs.

Fig. 4. Emulated world representations.

Note that UEs are not constrained within this 27 km^2 area thanks to a wrap around technique. When a UE is about to leave the emulated world by crossing one side, it reappears at the opposite side (still within the same cell if necessary), as they were somehow moving on a torus (Fig. 5).

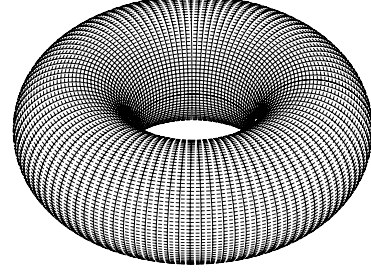


Fig. 5. Torus world.

The testbed supports up to 30 users by sector (up to 360 users in the entire emulated world). This number is fixed at the beginning of an emulation run and does not vary during it. We assume that the different UEs are switched on during the entire emulation. This means that we do not have any UE birth-death mechanism. However, their activity is controlled by the stochastic models of Section III. As a result, during an emulation with say 12 users, we may encounter periods of inactivity as well as full load periods when all 12 users are active.

This is illustrated on Fig. 6 which shows the aggregate downlink traffic of a given NodeB during an emulation of 1.200 seconds with 12 users. Up to three users are simultaneously streaming around the 600^{th} second whereas there was no traffic at all a few seconds before.

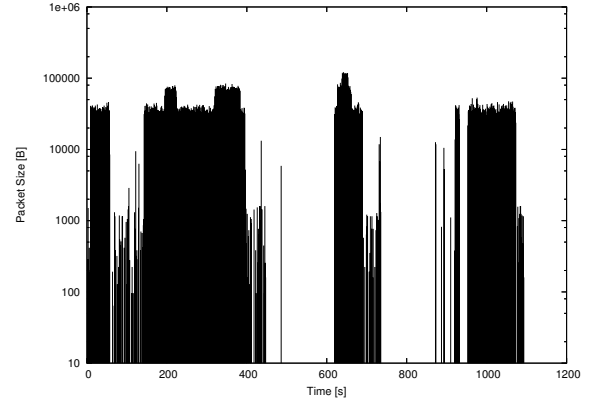


Fig. 6. NodeB downlink traffic.

B. Random Walk

To enable terminal mobility inside the testbed, we decided to focus on four specific UE speeds: 3 km/h representing a pedestrian walk, 30 and 70 km/h which represents a UE on board of a vehicle inside a city and 120 km/h which finally represents a UE embarked on a train or on a car on the speedway.

To describe the UE mobility, we opted for the Gauss-Markov mobility model [16]: every second, the distance the UE will cover and the direction it will follow during the next second are drawn randomly. Keeping in mind that a vehicle

moving at 120 km/h could not turn as abruptly as a pedestrian, the range of possible directions is then reduced with increasing UE speed. Fig. 7 illustrates the course of two different UEs respectively moving at 120 and 30 km/h during 600 seconds.

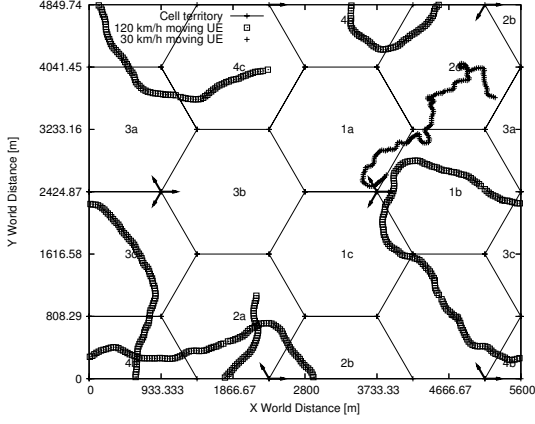


Fig. 7. Random walk at 2 different speeds.

C. Handovers

Now that our UEs are able to move, we have to establish a handover procedure which will decide where and when a handover has to be performed. This procedure is based on the Signal to Noise plus Interference Ratio (SNIR):

$$SNIR = \frac{Reception\ Power}{Interferences + Noise} \quad (1)$$

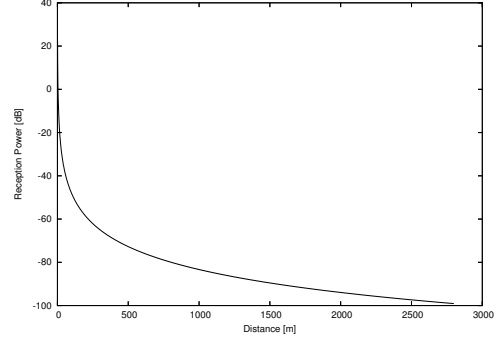
The computation of the reception power is based on the signal power received on a specific UMTS physical channel known as CPICH (Common Pilot CHannel). Our hypotheses concerning the CPICH as well as all the other testbed cellular parameters are summarised in Table III.

TABLE III
TESTBED CELLULAR PARAMETERS.

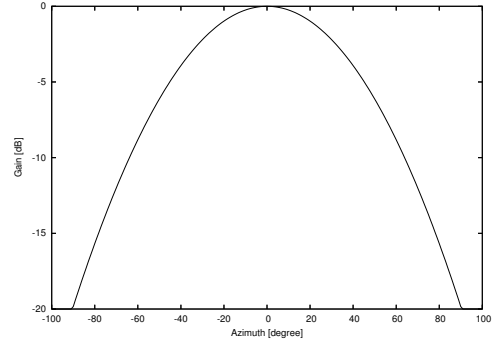
Parameter	Setting
Emission power [dBm]	43
Sectorial gain [dBi]	14
Noise figure [dB]	9
Thermal noise density [dBm/Hz]	-174
Emitting frequency [GHz]	2.14
NodeBs height [m]	30
UEs height [m]	1.5
CPICH spreading factor length [chips]	256
CPICH power [% of the total power]	10
SNIR handover threshold [dB]	4

The reception level is then emulated by a calculation mainly influenced by the distance separating the UE and its serving NodeB (*SNodeB*, the NodeB the UE is connected to), and by the angle created between the UE position and the *SNodeB*'s main emitting direction:

- The received power decreases as the distance between the UE and its *SNodeB* increases. This relation is known as path-loss and it is not a linear one (Fig. 8(a)). To model this, we use the Okumura-Hata wireless propagation equations and their UMTS adaptation [17].
- As shown on Fig. 8(b), if a UE is connected to a trisectorial NodeB, its received power will decrease as it will move away from the sector main lobe [18].



(a) Received power vs. UE – *SNodeB* distance.



(b) Antenna gain vs. UE – *SNodeB* angle.

Fig. 8. UE reception influencing factors.

Another concept, embedded in the WCDMA, influencing the UE reception level is the signal spreading [19]. It is able to amplify a signal and to attenuate the interferences. The higher the spreading factor is, the more amplified the signal will be (resp. the more attenuated the interferences will be) but the slower the sending of the data on the wireless interface will be. The spreading factor's choice is then a real challenge the RNC has to overcome.

In the testbed, the interferences are simply considered as the sum of the received power from the NodeBs but the UE *SNodeB*, multiplied by two. Indeed, we only have four NodeBs in our emulated world, but to compute a representative interference figure we have to take into account all the NodeBs lying around the *SNodeB*. In our hexagonal grid world representation, this means we have to consider six instead of three surrounding NodeBs.

As the noise level is assumed to be constant during an entire emulation, (1) finally becomes:

$$SNIR = \frac{S_{NodeB \text{ Rec. Pow.}} * SF_{CPICH}}{2 * (\sum Other \ NodeBs \ Rec. \ Pow.) + Noise} \quad (2)$$

Derived from (2), Fig. 9 represents the SNIR level map of our emulated world.

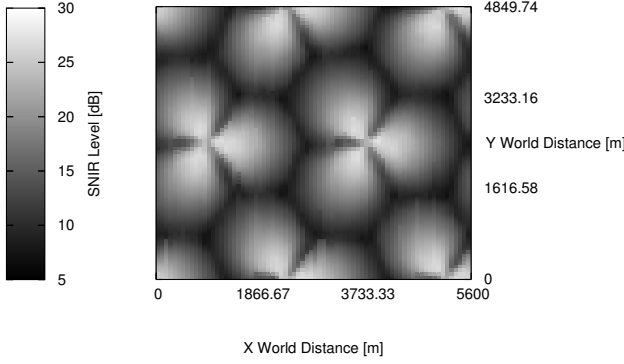


Fig. 9. SNIR map.

A handover occurs when the difference between the power of the S_{NodeB} 's signal and the power of another NodeB's signal is greater or equal to the handover threshold (Table III). Based on this continuous SNIR evaluation the RNC knows exactly when to handoff a UE.

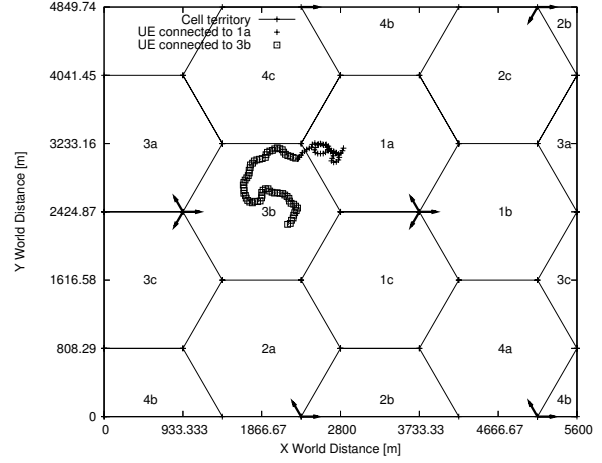
V. RESULTS

Using the previously presented modules (traffic generation, emulated world, random walk and SNIR computation), it is now possible to mimic in a realistic way what happens in a real UTRAN when a UE faces a handover. Fig. 10 illustrates the results from the working of the testbed. It represents the journey of one UE during 450 seconds generating and receiving conversational traffic only.

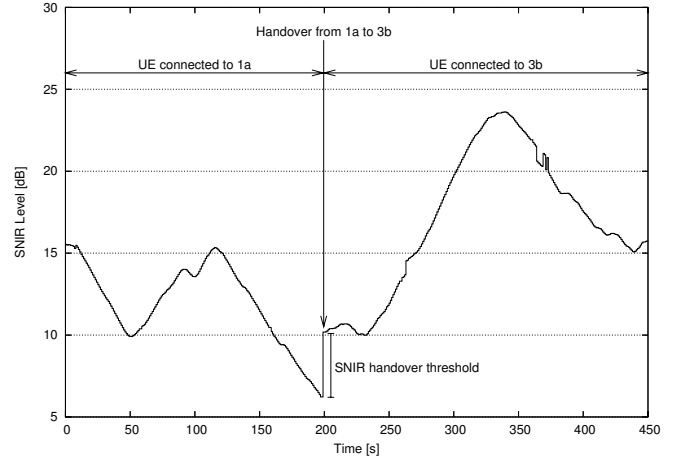
Thanks to the mobility graph of Fig. 10(a), we figure out that the UE undergoes a handover passing from the NodeB #1 (sector a) to the NodeB #3 (sector b) at about the middle of the emulation.

As we look at the SNIR evolution of the UE (Fig. 10(b)), we observe that the handover exactly occurs when the power of the signal received by the NodeB #3 (sector b) exceeds by 4 dB the signal received by the UE's S_{NodeB} power. It is indeed what we expected regarding the handover SNIR threshold value (Table III).

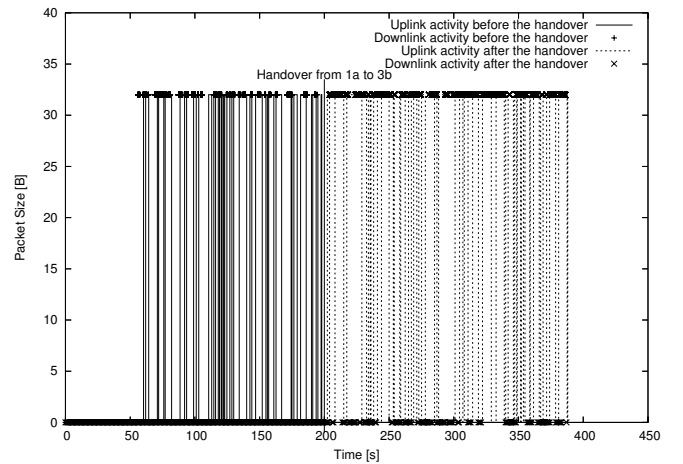
Finally, if we look at the activity graph of Fig. 10(c), we discover that the UE was active (sending/receiving data) when the handover occurred. We can clearly distinguish the end of the first connection and the beginning of the second connection, both totally synchronised in uplink and downlink directions.



(a) Mobility graph.



(b) SNIR graph.



(c) Activity graph.

Fig. 10. Handover impacts.

From the testbed point of view, this handover is translated by a process migration from a computer to another (Fig. 11): first of all, the traffic emitting processes have to be stopped on the source computers (the *C* computer and NodeB #1 i.e. the eastern computer of the *B* group), then new processes corresponding to the traffic generation after the handover can be started on the *C* computer and new destination computer (NodeB #3 i.e. the southern computer of the *B* group). As a result, the packets belonging to the same activity session do not use the same physical route after this handover. Consequently, we can say that our UMTS testbed supports UE mobility above a wired infrastructure.

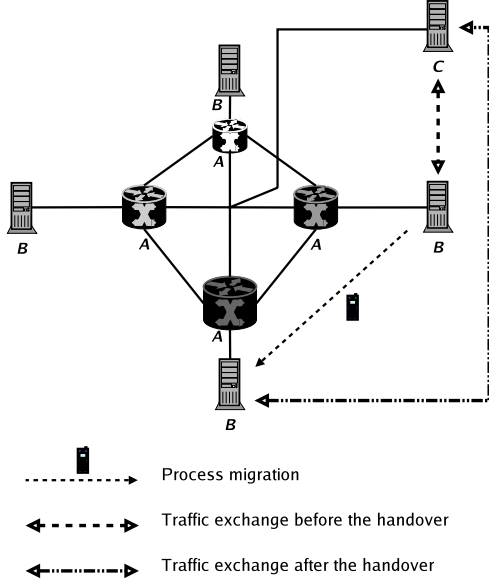


Fig. 11. Handover testbed's point of view.

VI. FUTURE WORKS

A. OVSF Tree Management

Following the WCDMA principles, before being able to send/receive any data, a UE needs to query a spreading factor. This will help to distinguish the UE's transmission from the other data transiting over the wireless interface. Our next step will thus be to take into account the constraints of the Orthogonal Variable Spreading Factor (OVSF) tree to allocate spreading factors to each user transmitting data over the wireless link. This allocation is established by the RNC and is based on the UE's user profile (platinum, gold, bronze or silver), traffic class (conversational, interactive, streaming or background) and SNIR level.

The RNC has to manage twelve OVSF trees, one for each sector in the emulated world, and tries to satisfy as many users as possible. In this way, a trade-off has to be made between allocating a high spreading factor to each user (which will lead to a spreading code starvation) and allocating a spreading factor to the greatest possible number of users (which will lead to users' general dissatisfaction).

A final OVSF issue the RNC has to overcome is to avoid allocation deadlocks. Because of its tree representation, the OVSF tree may have enough room to accept a new spreading factor but would still have to reject the query due to previous bad spreading factor placements [20].

B. Transport Channels Modelling

To transit over the wireless interface, the data may use different UMTS transport channels: the Dedicated CHannel (DCH), the Dedicated Shared CHannel (DSCH) and the Forward Access CHannel (FACH). Note that the emulation of a fourth transport channel, the High Speed-DSCH (HS-DSCH), is still under study for the time being. Based on the 3GPP standardisation [19], the channel used depends on the traffic class (Table IV) and, as for the spreading factor allocation, the channel assignment is decided by the RNC.

TABLE IV
TRAFFIC AND CHANNELS MAPPING.

3GPP Traffic Classes	Authorised Transport Channel(s)
Conversational	DCH
Interactive	DCH
Streaming	DCH or DSCH
Background	DCH, DSCH or FACH

Our idea is to introduce packet policing/sha-ping/scheduling at the NodeB level (A group computers) to emulate those different channels. To do so, we are thinking of using the Linux *TC* tool and the *traffic class* field of the IPv6 header to dynamically create hierarchical token buckets on each of the NodeBs (Fig. 12).

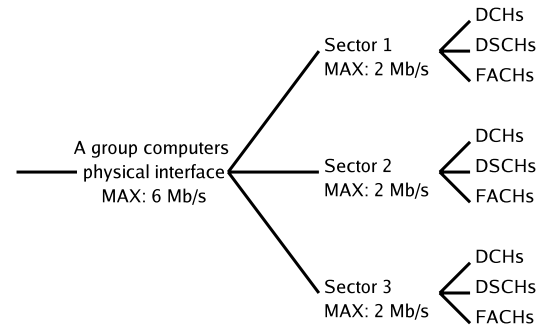


Fig. 12. Hierarchical token buckets.

The hierarchical property of the token buckets matters since it enables token borrowing between two buckets. We think here to apply this characteristic to the shared transport channels, namely the DSCHs and the FACHs.

C. Wireless Link

Finally, the wireless link emulation is also an important step since the testbed tries to emulate a UTRAN based on a wired network. Our ambition is use the freeware *Click Modular Router* [21] to insert an emulated RLC layer in

the conventional OSI model. It will take place between the MAC and the network layers and will support the three transmission modes (acknowledged mode, unacknowledged mode and transparent mode), the TTI scheduling (firstly 10 *ms* as in Rel' 99 and later 2 *ms* needed by the HSDPA) [19] and a random PER-driven packet dropping process based on the UE's SNIR level (since the UMTS wireless interface is much less reliable than a wired link).

VII. CONCLUSION

We have described our IPv6 Linux-based UTRAN testbed. We have exposed how we emulate a real UTRAN by means of different modules such as traffic modelling, random walk algorithm and SNIR level dependent handover procedure. We have also presented the first results obtained by combining all these modules about the handover management.

This project shows to which extend a rather simple testbed based on freewares and an open-source operating system can emulate a much more complex system. It is aiming at going open-source. However, as it is currently still in its infancy, such a move would be premature. Nevertheless, we are open to partnership. Meanwhile the status of the project can be checked on http://www.info.fundp.ac.be/~hvp/rech/doc/index_en.html.

REFERENCES

- [1] Quagga routing software suite. <http://www.quagga.net>, last visited: 04 January 2006.
- [2] Traffic generator tool. <http://www.postel.org/tg/tg.htm>, last visited: 04 January 2006.
- [3] Harri Holma and Antti Toskala. *HSDPA/HSUPA for UMTS: High Speed Radio Access for Mobile Communications*. Wiley inter-science, April 2006.
- [4] Technical Specification Group Radio Access Network. TS 23.107 V6.3.0, Quality of Service (QoS) concept and architecture. Technical report, 3rd Generation Partnership Project (3GPP), June 2005.
- [5] J.A. Aguiar and L.M. Correia. Traffic Source Models for the Simulation of Next Generation Mobile Networks. In *Proceedings of the 7th Wireless Personal Multimedia Communications (WPMC)*, Abano Terme (Italy), September 2004.
- [6] A.B. García, E. García, M. Álvarez-Campana, J. Berrocal, and E. Vázquez. A Simulation Tool for Dimensioning and Performance Evaluation of the UMTS Terrestrial Radio Access Network. *Lecture Notes In Computer Science*, 2515:49–60, 2005.
- [7] Alexander Klemm, Christoph Lindemann, and Marco Lohmann. Traffic modeling and characterization for UMTS networks. In *Proceedings of the 44th Globecom conference*, San Antonio (TX - USA), November 2001.
- [8] Y. Li Frank and Stol Norvald. QoS Provisioning using Traffic Shaping and Policing in 3rd-generation Wireless Networks. In *Proceedings of the 3rd Wireless Communications and Networking Conference (WCNC)*, Orlando (FL - USA), March 2002.
- [9] Soam Acharya and Brian Smith. An Experiment to Characterize Videos Stored on the Web. In *Proceedings of the 5th Multimedia Computing and Networking (MMCN)*, USA, January 1998.
- [10] A. Reyes, E. Gonzalez-Parada, E. Casilari, J.C. Casasola, and A. Díaz-Estrella. A page-oriented WWW traffic model for wireless system simulations. *Teletraffic Engineering in a Competitive World (ITC16)*, pages 1271–1280, 1999.
- [11] Technical Specification Group Radio Access Network. TS 30.03 V3.2.0, Selection procedures for the choice of radio transmission technologies of the UMTS. Technical report, 3rd Generation Partnership Project (3GPP), March 1998.
- [12] Technical Specification Group Radio Access Network. TR 25.896 V6.0.0, Feasibility Study for Enhanced Uplink for UTRA FDD (Release 6). Technical report, 3rd Generation Partnership Project (3GPP), April 2004.
- [13] Technical Specification Group Radio Access Network. TR 25.933 V5.4.0, IP transport in UTRAN (Release 5). Technical report, 3rd Generation Partnership Project (3GPP), January 2004.
- [14] Technical Specification Group Radio Access Network. TR 25.876 V1.7.1, Multiple Input Multiple Output in UTRA. Technical report, 3rd Generation Partnership Project (3GPP), October 2005.
- [15] Technical Specification Group Radio Access Network. TR 25.892 V6.0.0, Feasibility study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement. Technical report, 3rd Generation Partnership Project (3GPP), June 2004.
- [16] Alexandrosz Burulitisz, Sándor Imre, and Sándor Szabó. On the Accuracy of Mobility Modelling in Wireless Networks. In *Proceedings of the 39st International Conference on Communications (ICC)*, Paris (France), June 2004.
- [17] COST 231 Final Report. Digital Mobile Radio Towards Future Generation Systems. Technical report, COST 231, November 1999.
- [18] Spatial Channel Model AdHoc Group. Spatial Channel Model Text Description. Technical report, 3GPP & 3GPP2, April 2003.
- [19] Harri Holma and Antti Toskala. *WCDMA for UMTS*. Wiley inter-science, third edition, October 2004.
- [20] YeChee Tseng, ChihMin Chao, and ShihLin Wu. Code Placement and Replacement Strategies for Wideband CDMA OVFS Code Tree. *Management IEEE Transactions on Mobile Computing*, December 2002.
- [21] The click modular router project. <http://pdos.csail.mit.edu/click/>, last visited: 04 January 2006.